

Design, Modelling and Measurement of Hybrid Powerplant for Unmanned Aerial Systems (UAS)

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Abstract: Hybrid powerplants combining Internal Combustion Engines (ICE) and Electric Motor (EM) prime movers have been extensively developed for land and marine based transport systems. The use of such powerplants in airborne applications has been historically impractical due to energy and power density constraints. Improvements in battery and electric motor technology make aircraft hybrid powerplants feasible. This paper presents a technique for determining the feasibility and mechanical effectiveness of powerplant hybridisation. In this work a prototype Aircraft Hybrid Powerplant (AHP) was designed, constructed and tested. It is shown that an additional 35% power can be supplied from the hybrid system with an overall weight penalty of 5%, for a given UAS. A flight dynamic model was developed using the AeroSim™ Blockset in MATLAB® Simulink®. The results have shown that climb rates can be improved by 56% when using the hybrid powerplant concept, with a standard propeller design.

Keywords: Aircraft Hybrid Propulsion Performance Simulation

1 Introduction

Worldwide UAS development constitutes a significant aviation business growth segment. A large proportion of emergent platforms rely on propeller propulsion using powerplants sourced from COTS aeromodelling equipment. Compared to traditional aircraft powerplants, these units have significant disadvantages in operational utility and energy efficiency.

Some systems developers have successfully modified COTS aeromodel ICE powerplants to obtain excellent efficiency, however these units continue to be inflexible for a range of operational requirements (eg. manual starting, no in-flight re-start, fixed pitch propeller design). However it will be shown that even though there is an increased weight penalty, a suitable combination of ICE and EM powerplant configuration, particularly Brushless Direct Current Motors (BLDC) can potentially lead to overall improvements in range, endurance, and payload whilst simultaneously allowing greatly enhanced operational flexibility. The benefits include improved take-off and climb performance, significant electrical power generation, and electric-only stealth operation. In addition, the engine can be restarted remotely at any time, and the propeller may be used as a regenerative turbine as desired on descent.

Harmon *et al* [1] has investigated high level hybrid control schemes and Santangelo and Taylor [2] have investigated some aspects of engine management in a hybrid UAV powerplant context. There remains much scope for basic system optimisation techniques.

A parallel aircraft hybrid powerplant system is shown in the schematic representation in Figure 1. All of these components are already found on most operational UAVs. The particular sizing, control system and mechanical design of these items must be determined to suit an airframe and mission performance.

The AHP propulsion system consists of Battery, Motor, Fuel, Engine, Transmission and Propeller. These components must be modelled to characterise their individual performance in order to construct overall system characteristics. The important parameters are: Battery (Energy Density, Power Density, Mass, Charge efficiency), Motor (Torque and Power Curves, efficiency), Engine (Torque and Power curves, efficiency), Transmission (Layout, efficiency) and Propeller (Thrust Coefficient, Power Coefficient, efficiency).

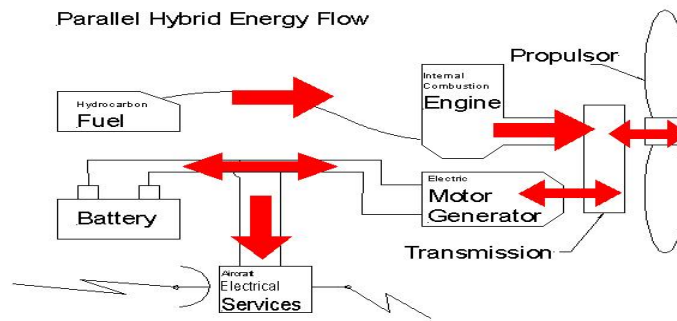


Figure 1. Parallel Aircraft Hybrid Powerplant Schematic

2 Experimental Design

Engine and motor performance analysis requires determination of maximum torque at a range of angular rates. Propeller experimental analysis requires measurement of torque, angular velocity, and thrust or drag at various airspeeds. A purpose built dynamometer was constructed to measure the shaft torque required from the propeller and that available from ICEs at various speeds. These variables were analysed using Load Curve plotting techniques.

The following section describes the experimental setup and results obtained from measurements of a specific propeller and motor configuration.

2.1 Experimental setup

In this experiment, measurements were obtained using a Mutunuc 10cc engine, which was mounted on a low-friction spindle restrained by a custom built load cell (Figure 2). Strain gauge readings as well as RPM data from a photo-diode were recorded on a Yokagawa scopecorder and later processed in MATLAB® to generate graphs. Torque curves for a Garvon 20"x6" propeller were measured in a similar way, using a wind tunnel to simulate forward aircraft velocity. The reaction torque through a range of angular rates at two forward velocities (static and translational) were recorded and two torque curves were generated.

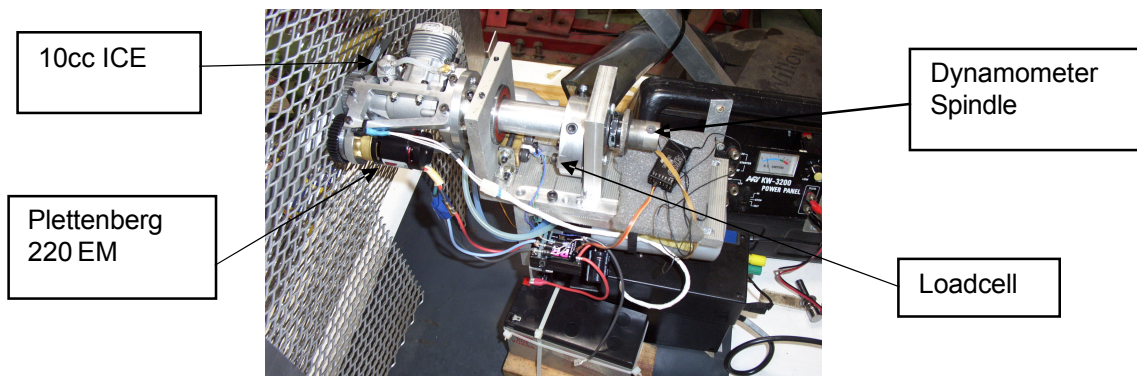


Figure 2. AHP on Dynamometer

A key tenet of the expected improvement in propulsive efficiency derives from the change of C_T and C_Q , the Coefficient of Torque, with Advance Ratio, J . The reduction of the thrust and torque coefficients with J can induce an increase in engine RPM in transition from static and slow speed flight to cruise and high speed condition. The engine torque curve will define the resultant value of J for any power setting giving a particular airspeed, since the propeller torque will always tend toward balancing the engine torque. If a larger propeller can be driven at static and low speed conditions with the aid of motor boost power, at cruise speed, this same propeller may be driven from engine power alone, or at a speed where some excess engine power may be diverted to electrical services or storage.

The dynamometer results are intended to validate the theoretical load curves in Figure 3 and Figure 4 below.

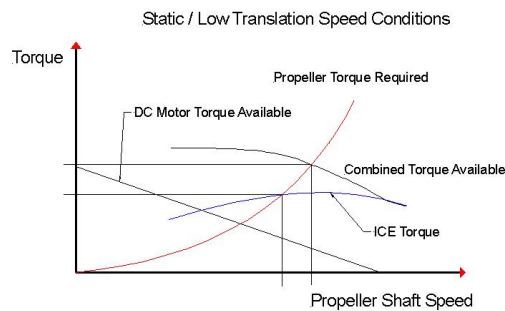


Figure 3. Expected Load Curve at Static/Low Translation Speed Conditions

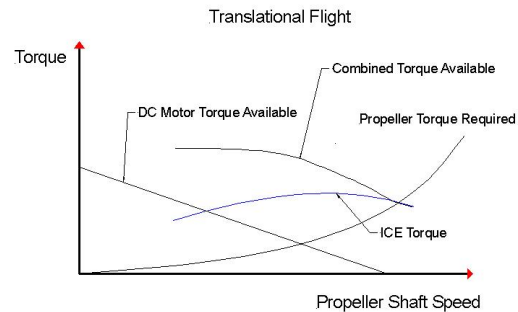


Figure 4. Expected Load Curve for Translational Flight

The torque required from the EM to enable the 20"x6" to be driven by the 10cc ICE for the static and translational conditions was to be determined in order to specify the EM required.

2.2 Experimental Results

Figure 5 shows the torque curves for the propeller (540mm static and 540mm translational) and the 10cc 2-stroke ICE. The 10cc engine under consideration is designed to drive a 300mm diameter propeller. It can be seen that for this combination of ICE and 540mm propeller there is never sufficient ICE torque available to supply the propeller torque required. The EM characteristic required for this engine to drive a 540mm diameter propeller, can be derived from the difference in the ICE torque available curve and propeller torque required curve, a representative EM characteristic torque curve (BLDC Torque required for 10cc ICE) for this situation is shown. This combination would represent an extreme case with a very high degree of hybridisation. The 10cc ICE cannot operate the specified propeller by itself; it requires the torque addition from an EM. The Aerosonde™ 25cc 4-stroke ICE torque curve is also shown for comparison. This engine can be seen to be capable of operating this propeller adequately without electrical boost. While the torque available is higher than the torque required, the angular rate can increase. The point at which these curves intersect indicates the operating point (maximum RPM) for these conditions, and therefore the maximum Thrust Available. Beyond this point there is less torque available than required and therefore the only way of increasing the RPM is by applying extra torque from the EM. With the application of EM boost torque it is possible to increase the ICE RPM into the best ICE operating range.

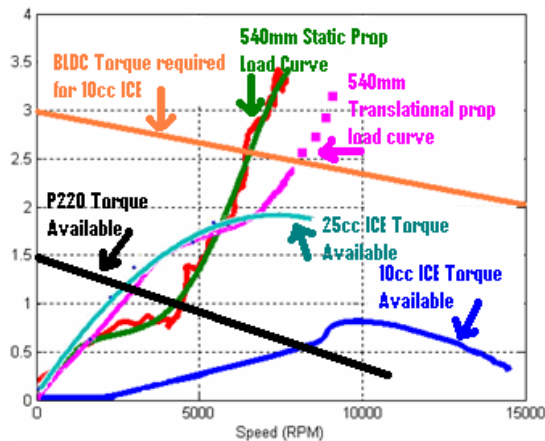


Figure 5. Experimental Load Curves

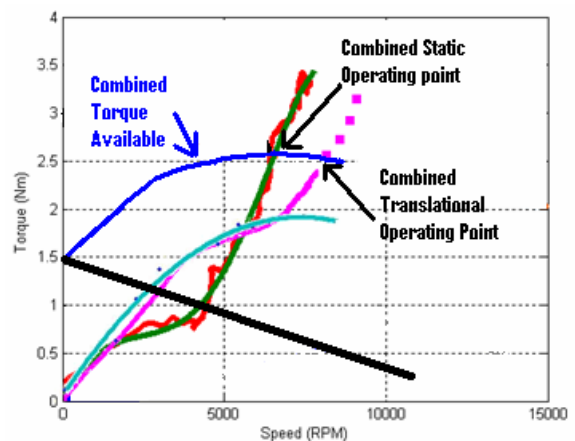


Figure 6. Experimental Load Curves

Figure 6 shows that the application of boost torque from a Plettenberg 220 EM will give significant excess torque through to a shaft speed of 7000RPM at static conditions. This would deliver much improved thrust and therefore take-off and climb performance. At cruise condition, the propeller torque required curve (540mm Translational prop load curve) has shifted to the right. Thus the maximum combined torque available allows higher RPM and thrust for higher flight speed or the generator mode may be employed to take advantage of the excess engine torque available.

On the basis of this analysis, very high thrust output for take-off and climb, significant charging power at low speeds, engine-only operation at moderate speed, and electric-only operation at slower speeds, for a given airframe, is achievable. In addition, the engine can be restarted remotely at any time, and the propeller may be used as a turbine as desired on descent.

3 Scenario Modelling

To validate the AHP propulsion system, improvements in the aircraft's range, endurance, and payload will be shown in comparison to existing powerplants, in simulation. Any aircraft performance outcomes are directly related to the mission requirements, therefore some certain operations shall be defined for a particular aircraft. For this purpose, mission scenarios shall include the basic aircraft operations such as Take-off, Climb, Cruise, Descent and Landing, as well as likely mission requirements such as payload and speed requirements. Ultimately, comparisons of the differences in energy and mass properties between the different powerplant systems shall be made.

3.1 Simulation Set-up

In order to feasibly test the widest range of mission scenarios, computer simulations were used. The MATLAB® Simulink® simulation environment combined with the AeroSim Blockset [5] offers a comprehensive aircraft simulation and analysis package [6]. Furthermore, a detailed model of an Aerosonde™ UAV, a real-world UAS, with a complete set of parameters is available. This model was utilised in the construction of the simulation model, shown below in Figure 7, which has the addition of an AHP prototype and aircraft control modules for unmanned operations. The AHP prototype includes the Aerosonde™ engine and a Plettenberg HP220/25 motor [7] with constant 18V input, and the required current is assumed to be provided. For comparison purposes, the simulations utilise the Aerosonde™ engine as the conventional powerplant.

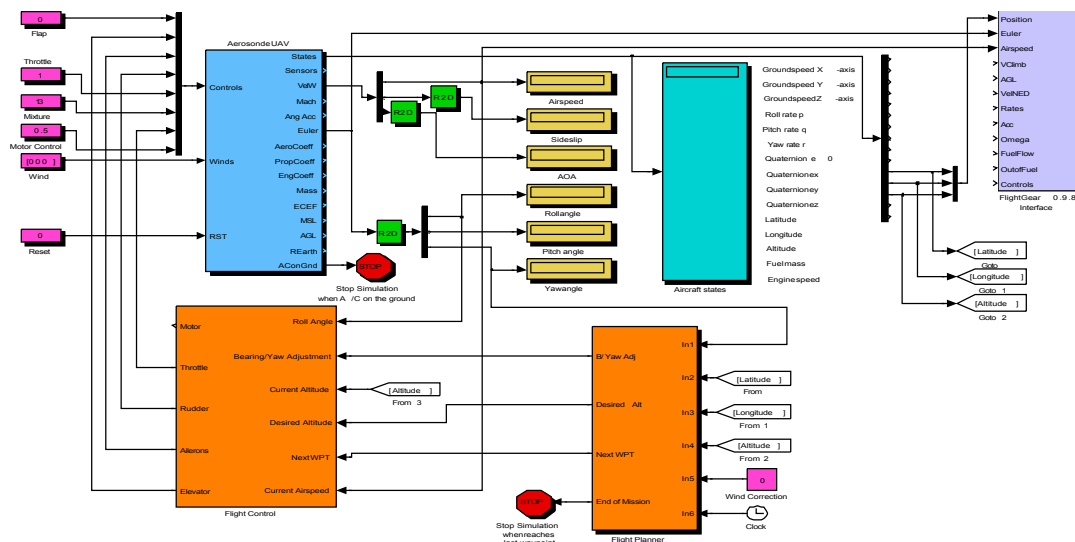


Figure 7. The Simulation Model

As a preliminary performance comparison of the AHP and ICE, the simulation model was set up to determine the rate of climb and time required to reach a designated altitude, given the different powerplants used. For each case, the aircraft travels with a constant heading at a fixed airspeed of 20m/s, climbing from an altitude of 300m, with a maximum power setting, up to 1000m. The results of the simulations are shown in the following section.

3.2 Simulation Results

Data generated from the execution of the simulation model given the above-mentioned scenario were formulated into the following graph. Figure 8 shows the aircraft altitude with respect to time for the ICE and AHP.

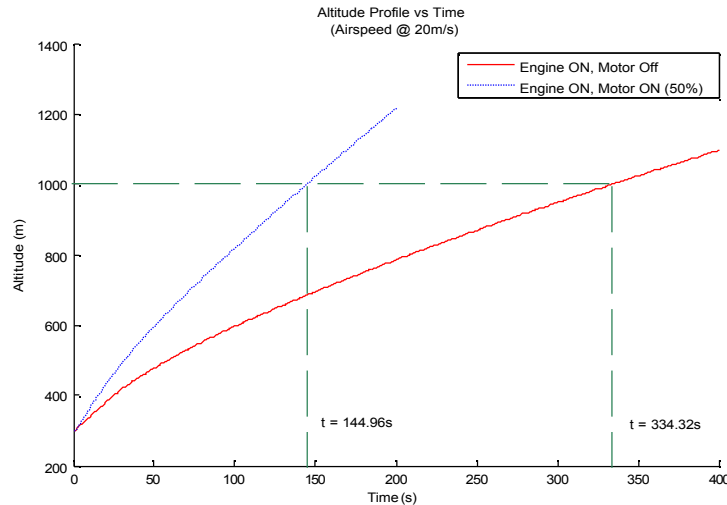


Figure 8. Altitude profile vs time graph for both AHP and ICE powered simulations

It is evident from the above graph that the climb rate for the AHP-powered Aerosonde™ is significantly greater than that of the ICE-powered version. The time required for the AHP to reach the designated altitude of 1000m (144.96s) is less than half that of the ICE (334.32s), which is an improvement of 56%.

The electrical energy used for the climb amounts to 26.3Wh. Assuming an overall EM system efficiency of 80%, the battery weight required to store this energy would typically be around 0.5kg for a NiMH battery with practical energy density of 70Wh/kg. The aircraft type in simulation had an all up weight of 14kg.

3.3 Discussion

The result of this basic simulation concurs with one of the major reasons for using an AHP propulsion system onboard an UAV. As expected the extra power provided by the electric motor was able to significantly increase the aircraft's climb rate and thus reduce the time required to reach a given altitude. Thus far, the simulation model block setup provides a reasonable output, on given parameters. However, this simulation was carried out with the assumption that the required voltage and current can be supplied continuously and has yet to take the battery component of the AHP system into consideration. The inclusion of the battery and associated components will constitute the next stage in the development of the simulation model, then further development will enable extended scenarios.

4 Conclusions and recommendations

The foundation for analysis, development and verification of an improved UAS propulsion system has been laid. A combination of empirically measured data, classical and modern analytical processes can be used to predict performance outcomes and guide system design.

Improved propulsion energy management, storage and delivery systems for UAS can yield a variety of beneficial outcomes. The sizing and matching of prime movers such as EMs and ICEs with propellers to suit specific operational requirements can be simplified by utilizing load curve techniques. Larger diameter fixed pitch propellers with higher propulsive efficiency can be used across a higher range of aircraft speed, than possible with normally aspirated ICE only powerplant.

Future work will refine propeller, engine and airframe empirical analysis with better experimental apparatus. Also the computer simulation systems for all these items will be enhanced and integrated. Improvements to the accuracy and precision of both these forms of analysis can then be made by reference to the resulting real world aircraft performance.

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